

LEAN BURN COMBUSTOR TECHNOLOGY
AT GE AIRCRAFT ENGINES

W.J. DODDS

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In late 1990 GE Aircraft Engines (GEAE) and Pratt & Whitney (P&W) agreed to a joint effort to conduct studies, acquire technology and validate capabilities and limitations of advanced low NO_x combustor concepts with the goal of generating information necessary for concept downselect in 1992. It has been agreed that P&W will have primary responsibility for demonstration of a rich burn quick quench combustor, while GEAE will concentrate on development of a lean burn combustor. In the lean burn program, both lean premixing prevaporizing (LPP) and lean direct injection (LDI) designs will be investigated (Tacina, 1990).

One key objective of these parallel programs is, by the end of 1991, to demonstrate a NO_x emissions index of 3 to 8 g/kg at HSCT cruise inlet conditions in simplified cylindrical combustors representing each of the concepts. The second objective, to be accomplished by the end of 1992, is to complete analyses and sector combustor tests necessary to assure that there are no fundamental limitations or technology barriers that would preclude successful evolution of a flightworthy combustor based on either of the basic combustor concepts.

This presentation summarizes progress to date at GE Aircraft Engines in demonstration of a lean combustion system for the HSCT. These efforts have been supported primarily by NASA contracts, with the exception of initial size and weight estimates and development of advanced diagnostics which have been conducted under GE Independent Research and Development projects. Key accomplishments to date are summarized below.

Lean Combustion Progress to Date

- **Identified combustor concepts - projected emissions, size, weight and performance impacts (3/90).**
 - **Predicted benefits of advanced materials and variable geometry (8/90).**
 - **Assessed/developed analytical capabilities for combustor design (CFD, chemical kinetics) and established design criteria (1/91).**
 - **Conducted cold flow mixing tests to identify preferred fuel injection location and verify CFD predictions (12/90).**
 - **Developed improved diagnostics (NO₂ LIF AND Laser Raman) for combustor development (3/91).**
 - **Initiated single cup rig tests to demonstrate 3-8 g/kg NOx at HSCT cruise by late 1991 (4/91).**
 - **Completed initial aero flowpaths for HSCT combustor and began mechanical design and control studies (5/91).**
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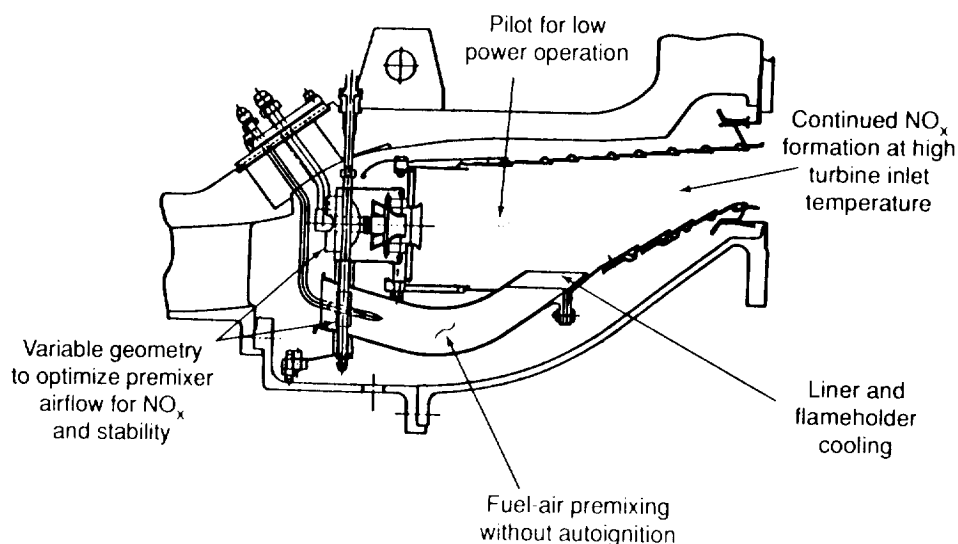
Figure 1 illustrates a parallel staged LPP combustor. A conventional pilot in the outer annulus is used for low power operation. A premixing main stage in the inner annulus is used at high power conditions.

The most challenging aspect of a LPP combustor for an HSCT engine is to obtain adequate premixing for low NO_x emissions without encountering precombustion in the mixer due to autoignition or flashback. If mixing is incomplete, NO_x will be formed in locally rich (near stoichiometric) regions of the combustion zone. Combustion within the mixer will, at best, result in increased NO_x, and could result in hardware damage to mixing ducts and flameholders.

A second major challenge is to maintain stable operation across the combustor operating range. To provide low NO_x, the premixing stage must operate very close to the lean stability limit. Local fuel-air ratio must be closely controlled with the use of fuel staging and airflow modulation to maintain stable operation.

At projected HSCT engine cruise conditions, combustor temperatures are so high that virtually all of the combustor airflow must be premixed with the fuel to achieve the NO_x goals. Thus, liner and flameholder cooling, as well as pilot stage airflow, must be minimized by using advanced materials for reduced cooling and variable geometry features to shut off pilot air at cruise conditions. Even when premixing airflow is maximized, it is critical to minimize residence time in the combustion chamber because NO_x formation rates are high even at projected combustion exit temperatures. Combustion zone residence time must be long enough to complete combustion without excessive NO_x formation.

LPP Combustor Design Issues



Roffe and Venkataramani (1978) have demonstrated that NO_x levels well below current goals can be achieved at representative HSCT cruise conditions with a well premixed system using prevaporized fuel (propane). Implementation of this technology into a liquid fueled system capable of full range operation is the present challenge.

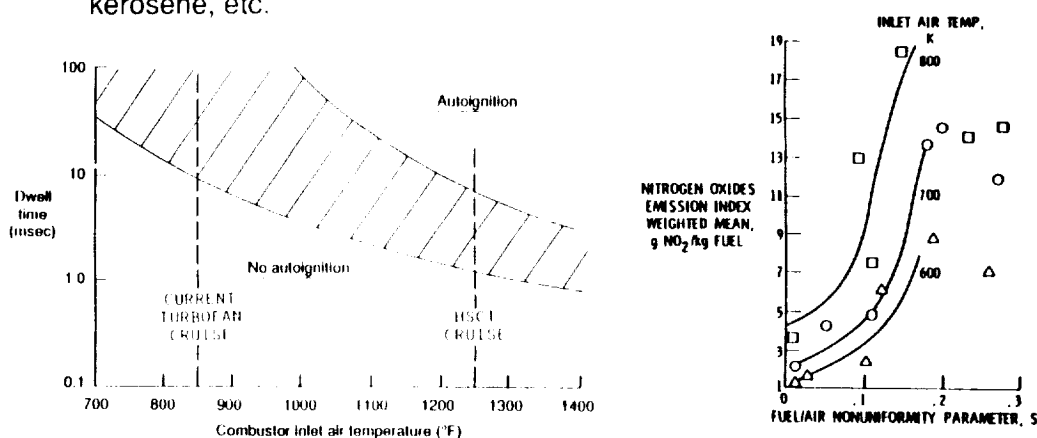
As indicated in Figure 2, at typical cruise conditions in current turbofan engines, it would take approximately 10 milliseconds for jet fuel to autoignite. This is of the same order as combustor residence times in current aircraft engine combustion systems, and is sufficient to achieve complete fuel-air mixing. However, projected HSCT cruise inlet temperatures are up to 400°F higher than those of current engines, leading to an order of magnitude reduction in available mixing time. Achieving full vaporization and thorough fuel-air premixing within 1 ms is extremely challenging.

As shown in Figure 2 (Lyons, 1979) NO_x levels are increased substantially if mixing is not complete. Thus, the major challenge of the LPP development effort is to obtain complete mixing without autoignition.

LPP Combustor Fuel-Air Mixing Issues

- Combustor inlet air pressure: 15 atmospheres liquid fuel data jet A, kerosene, etc.

- Nominal equivalence ratio of 0.6



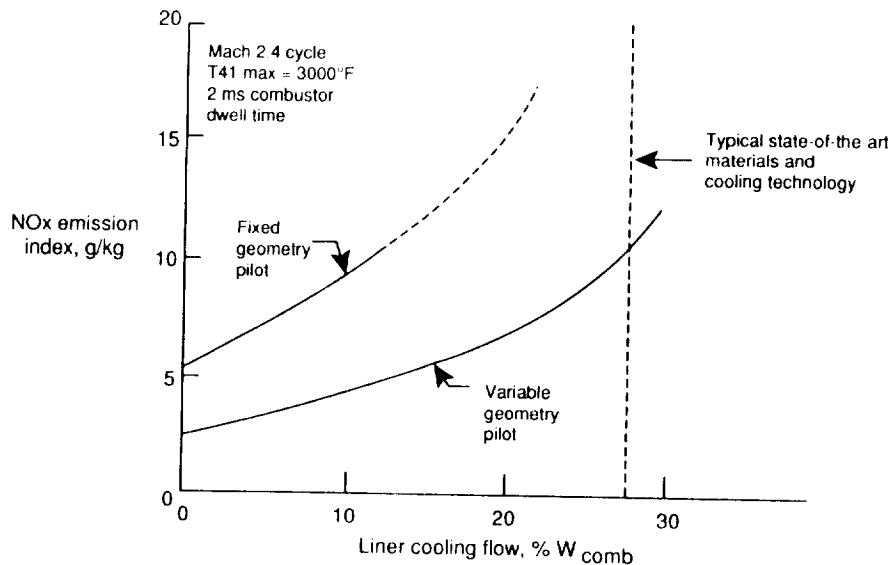
Need to Fully Mix in Less Than 1 MSEC

The importance of new technologies including advanced materials and variable geometry devices which can be used to maximize premixer airflow are illustrated in Figure 3. These NO_x emission estimates were based on results of research combustor tests at representative HSCT cruise conditions with well premixed propane flames (Roffe and Venkataramani, 1978). As indicated, a premixing combustor with fixed geometry and conventional liner cooling levels would produce NO_x levels above 20 g/kg because the premixing stage would operate at relatively rich conditions with the available airflow. Use of variable geometry to force more air into the premixer would reduce NO_x to about 10 g/kg, still above the goal.

With the use of variable geometry and elimination of liner film cooling, levels of about 2 g/kg are predicted. Recall, however, that NO_x levels could be somewhat higher than indicated due to the challenge of premixing at HSCT combustor inlet conditions.

Elimination of liner film cooling is also important in order to reduce quenching of CO near the combustor walls. Roffe and Venkat Raman (1981) have illustrated that wall quenching can adversely affect CO burnout.

Effects of Variable Geometry and Liner Cooling on LPP NO_x

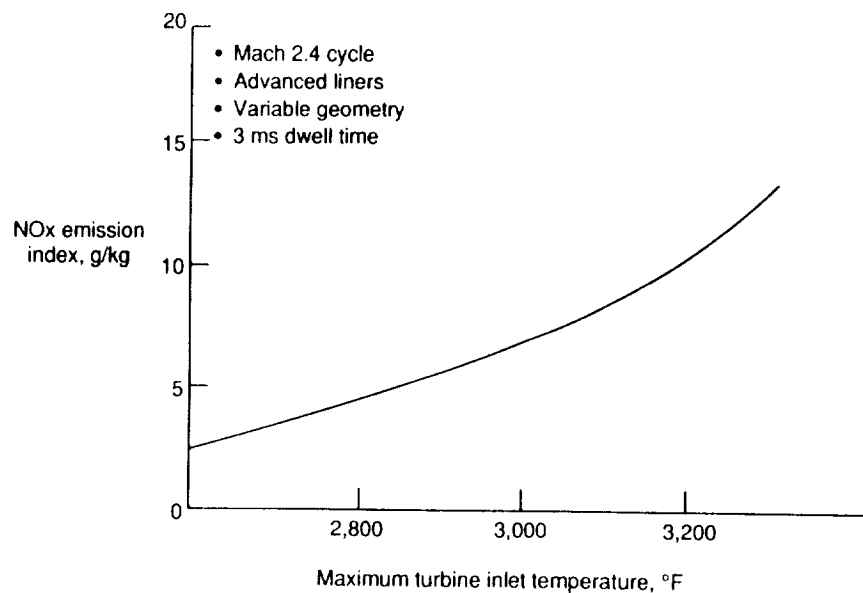


*Variable Geometry and Advanced Materials
Needed to Meet NO_x Goals*

A rule of thumb for low thermal NOx production is to keep local temperatures below 3000°F. This is in the range of steady state turbine rotor inlet temperatures at projected HSCT cruise conditions. Temperatures are even higher within the combustor, prior to addition of turbine nozzle cooling airflow. Thus, it is very important to minimize post-flame dwell time between the reaction zone and the location in the turbine nozzle where the flow is accelerated to the point that thermal NOx formation rates become negligible.

Cycle conditions are also critical to NOx production. As indicated in Figure 4, an increase of 200°F in turbine inlet temperature will nearly double NOx emissions.

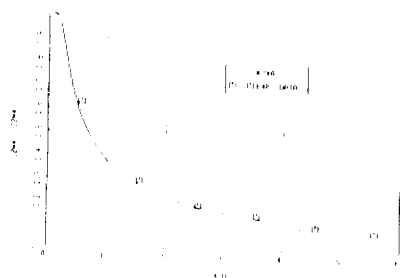
Cycle Turbine Inlet Temperature Effect on LPP NOx



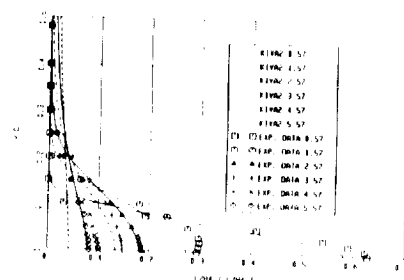
Engine Cycle Affects NOx Capability

Currently available computational fluid dynamics (CFD) codes and chemical kinetic codes have been developed and evaluated to the point where they are quite useful for LPP combustor design. Figure 5 shows a few examples that verify the usefulness of these approaches. As shown, fuel-air mixing in a duct premixer was predicted quite well with KIVA code computations. NO_x and CO chemical kinetics models also agree well with data for lean premixed systems. The example shown uses the kinetic scheme of Bittker et al. in a reactor network model to predict both prompt and thermal NO formation. Results are in good agreement with premixed combustor data. Chemical kinetic ignition delay computations based on a model developed by Jachimowski (1984) have been used to estimate the effects of inlet pressure, temperature and equivalence ratio on ignition delay. Results of these computations have been used to define and refine criteria for premixer and combustion chamber designs.

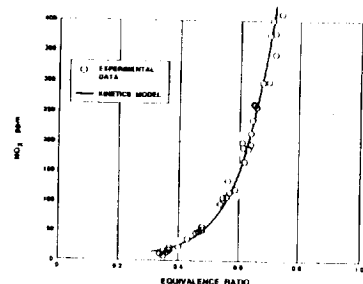
Analytical Capabilities



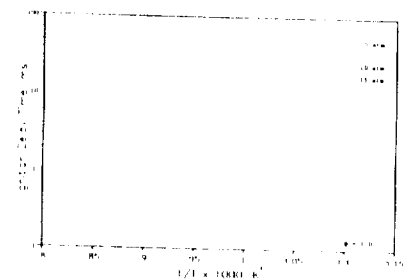
Fuel-Air Mixing in Duct
(Centerline Concentrations)



Fuel-Air Mixing
(Radial Profiles)



NO_x/CO Kinetics



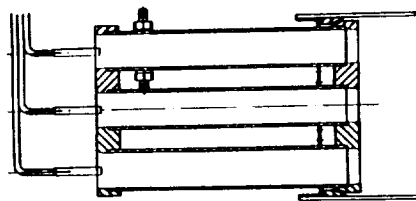
Autoignition Kinetics

The three general types of premixers shown in Figure 6 are being evaluated for use in an engine design. The duct premixer shown is a variation of the multiple tube injector that has been widely used in fundamental studies of LPP combustors. The design consists of several cylindrical air ducts. Fuel is injected near the entry of each duct, and the fuel and air mix within the duct. The flame is stabilized by a rapid expansion at the duct exit.

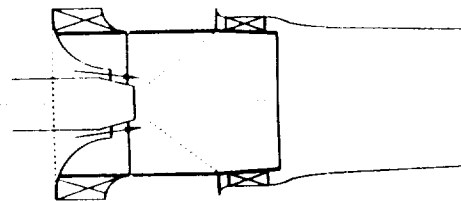
The second type of premixer uses a larger duct with a device to swirl the airflow at the inlet. Fuel is injected at the center of the vortex, and the swirling flow promotes fuel-air mixing. The duct is sized for high axial velocity, and relatively low swirl is used to prevent recirculation on the duct centerline, which could lead to flashback. The flame is stabilized at the premixer exit by the recirculation zone set up by the swirling flow.

The third fuel preparation concept is a lean direct injection device. In this device, equal portions of fuel are injected into each of many small air jets. Although the length of the air passages is not sufficient to provide complete fuel-air mixing, the design objective is to make the scale of the jets very small so that fuel-air mixing rates in the combustion zone are fast enough to provide very low NO_x levels (Hussain et al., 1981).

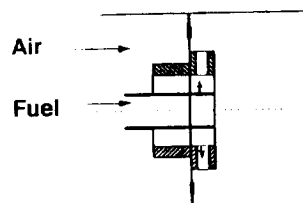
Premixer Concepts



Duct Premixer



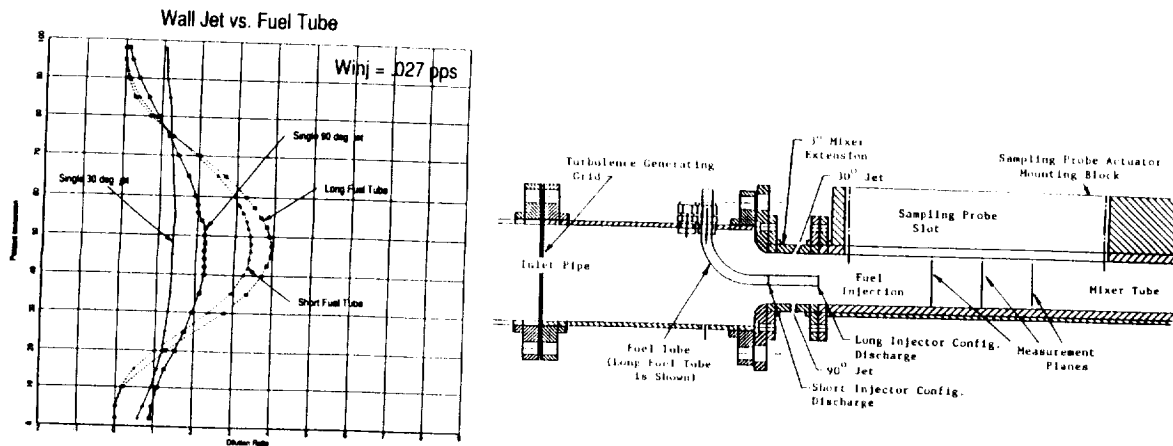
Swirl Premixer



Lean Direct Injection Flame Stabilizer

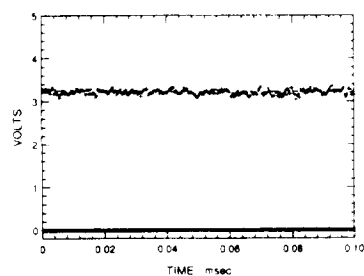
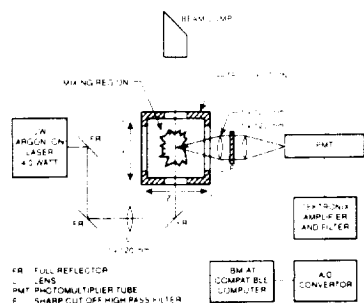
Cold flow mixing tests have been initiated to investigate different fuel injection schemes for a duct-type premixer. A large scale (approximately 5X) mixing duct has been evaluated, as shown in Figure 7. Mixing of simulated fuel and air streams has been evaluated using an ethylene tracer gas technique described by Mehta et al. (1989). These tests have been used to establish a preferred fuel injection approach for combustion tests of the duct premixer.

Cold Flow Mixing Test

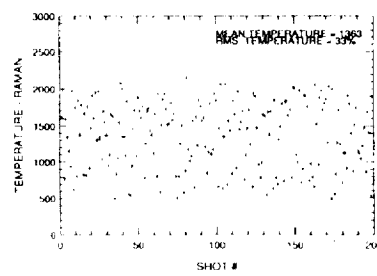


The ethylene tracer technique employed in these initial tests is useful for measuring time-averaged fuel-air mixing. However, time variations in fuel-air mixture uniformity (unsteady flow effects) can lead to increased thermal NO_x formation. In order to evaluate these unsteady effects at GEAE, NO₂ laser induced fluorescence capability has been developed for cold flow mixing tests and a spontaneous Raman system has been developed to measure average and fluctuating temperature and major species concentrations in methane flames (Figure 8). Additional work is in progress to evaluate the Raman technique in flames where distillate fuels are used.

Diagnostics Developments (GE CR&D)



NO₂ Laser Induced Fluorescence



Raman - CH₄ Flame

A cylindrical combustion test rig sized for evaluation of one full scale swirl premixer or LDI device has been built. For duct premixers, a sector or arrangement of premixers equivalent in airflow to a single swirl premixer is evaluated, as shown in Figure 9.

The objective of these single premixer combustion tests is to evaluate different premixer and fuel injector design configurations and establish effects of parametric changes in design features such as premixer length, direction of fuel injection, or combustor residence time. Fuel injector/mixers representative of engine designs are being evaluated for emissions (NO_x, CO, UHC), flame stability and lean blowout, flashback/autoignition, and ignition/flame propagation characteristics.

Typical test conditions for initial low pressure tests will be a pressure of 15-60 psia, inlet temperature of 800-1000° F, combustor residence time of 1 to 3 ms and equivalence ratios from 0.70 to the lean limit. High pressure tests of the most promising configurations will then be conducted at pressures up to 300 psia and inlet temperatures up to 1200° F to evaluate operation at actual HSCT engine operating conditions.

High Temperature and Pressure Duct Premixer Rig

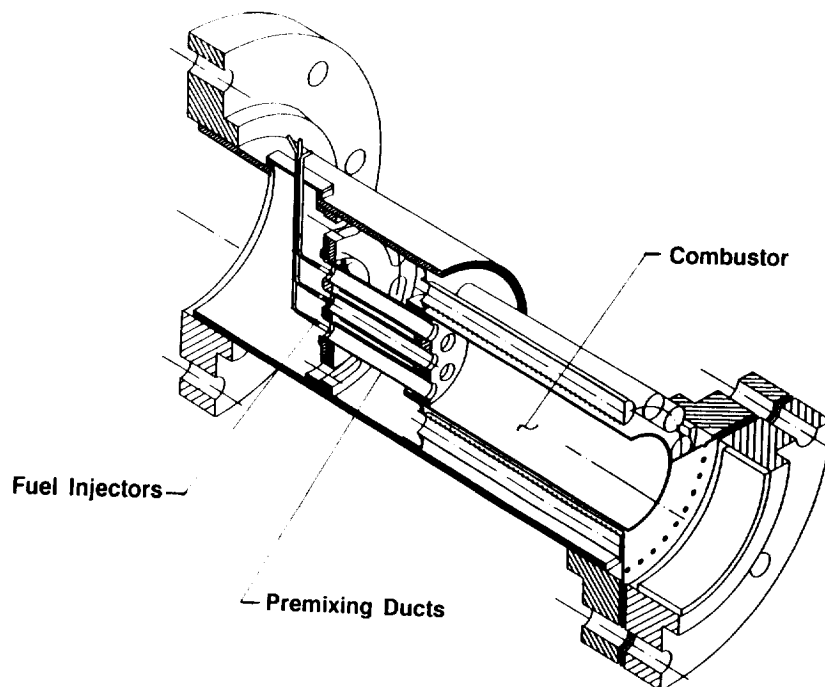
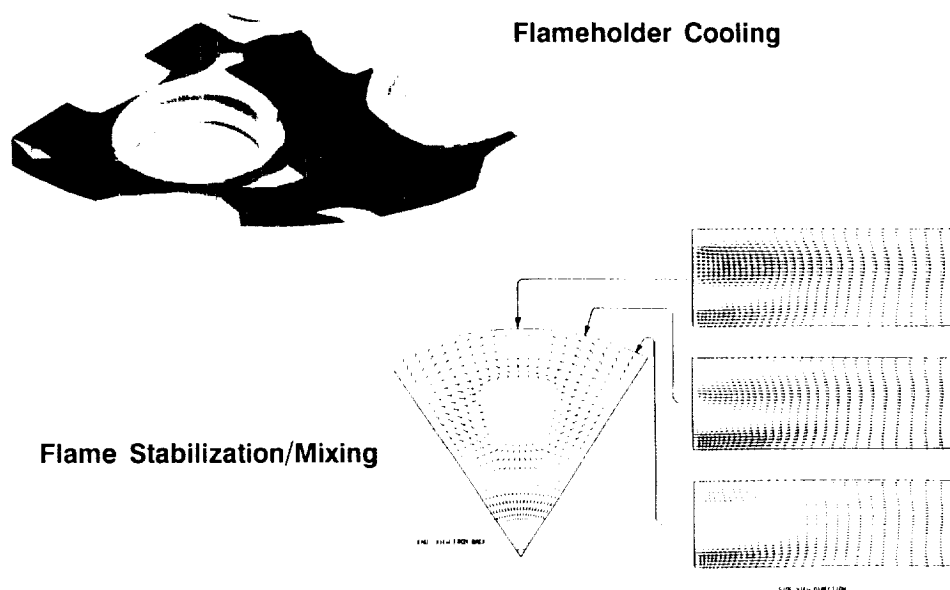


Figure 10 illustrates two of the design issues that were addressed during design of the cylindrical rig. Flameholder cooling is accomplished with backside impingement, while ceramic thermal barrier coatings are used to protect the surface that is exposed to the flame. Finite element heat transfer and stress analyses were conducted which indicate that flameholder durability will be acceptable with this design approach.

CFD analysis was used to evaluate recirculation patterns and mixing in the combustion zone downstream of the flameholder. The GE CONCERT code premixed combustion model is currently being adapted to compute NO_x formation for this flameholder configuration.

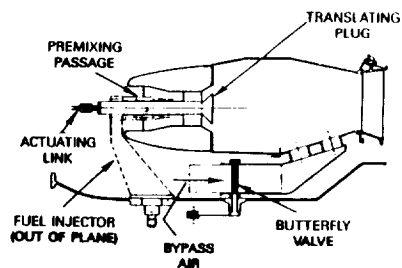
Duct Premixer Design Considerations



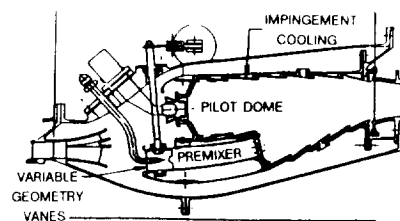
Flowpath layout studies are currently underway to define LPP and LDI systems suitable for full range operation in an HSCT engine. Combustor inlet conditions and compressor and turbine interfaces have been identified based on the most recent engine cycle studies being conducted at GEAE.

Any one of many different design concepts could potentially be used. Three options, based on previous design and development programs, are shown in Figure 11.

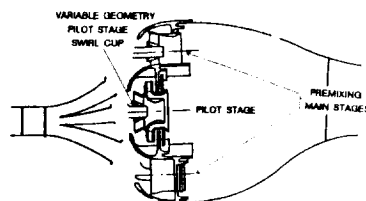
LPP/LDI Combustor Concepts



A. Single annular/wide V-G



B. Parallel staged/2-stage V-G



C. Three stage/pilot V-G

Sector combustor tests will be conducted to evaluate two selected combustor configurations and establish effects of key design and operating parameters on NO_x emissions and combustor performance. A sector combustor and test rig similar to those shown in Figure 12, incorporating all key features of an engine combustor design will be fabricated and tested to evaluate the influence of engine hardware features such as dilution holes/wall cooling, fuel-air staging and variable geometry features on emissions, exit temperature profiles, flashback/autoignition, hardware temperature and stability limits.

Two types of tests will be conducted. Initial screening will be done in low pressure tests (15-60 psia pressure and 800-1000° F inlet temperature). High pressure tests (200-300 psia maximum pressure and up to 1200° F inlet temperature) will then be conducted to evaluate emissions and autoignition of promising combustor configurations at full engine pressure.

Typical Combustor Sector Test Rig



Combustor



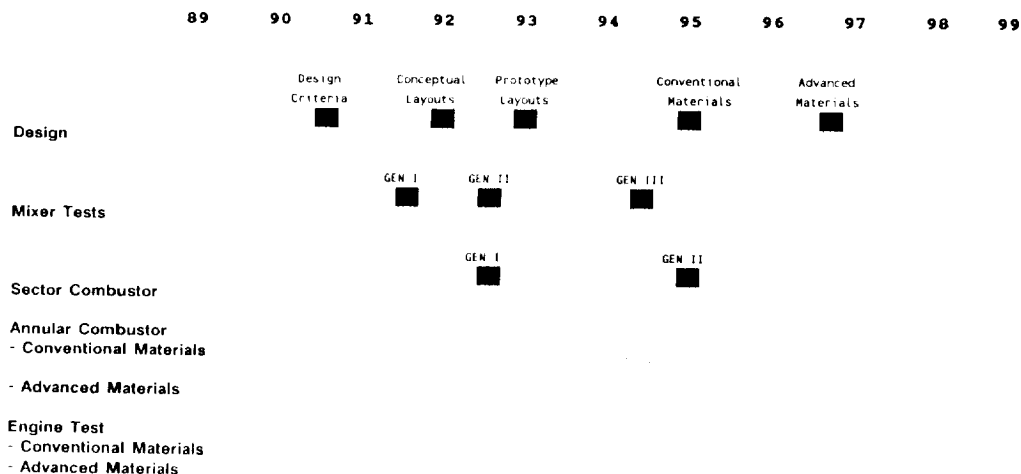
Rig

Elements of the long term HSCT combustor development plan are shown in Figure 13. The current NASA-supported work, through 1992, will include initial sector combustor tests to verify NOx emission reduction capability and identify potential technology barriers that would preclude their successful development. The next step would be to build an annular prototype of the most promising combustor design to develop and refine combustion steady state operating capability over the full range of combustor operating conditions from lightoff to maximum thrust. The objective of these annular tests would be to evolve, by the end of 1994, a combustor design capable of meeting the NOx emissions goal and providing adequate operability, performance and durability for a demonstrator engine test in an existing engine that could be operated at combustor inlet temperatures and pressures representative of the range of HSCT engine operation.

An engine quality combustor would then be built, using conventional materials, for an initial engine demonstration in 1997. The primary purpose of this engine test would be to evaluate transient response of the combustor (including fuel staging and variable geometry features) and evaluate NOx emissions in the presence of interactions with an actual engine compressor and turbine.

As indicated earlier, high temperature materials are needed to meet the HSCT NOx goals with good long-term durability. Active development of needed materials will proceed in parallel with the combustor development efforts. However, these materials will not be available for initial annular combustor rig engine tests. Combustors built with conventional materials for these early tests might rely on auxiliary cooling to permit demonstration of emissions and performance capabilities. As the advanced materials become available, a second set of rig and annular tests would be conducted to demonstrate the full potential of the evolved combustor design with combustor components which use the best of the high temperature materials.

HSCT Combustor Development Plan



REFERENCES

- Bittker, D.A. and Scullin, V.J., "GCKP84 - General Chemical Kinetics Code for Gas Phase Flow and Batch Processes Including Heat Transfer Effects," NASA-TP-2320, 1984.
- Hussain, U.S., Andrews, G.E., Cheung, W.G. and Shahabadi, A.R., "Low NOx Primary Zones Using Jet Mixing Shear Layer Combustion," ASME 81-GE-308, 1981.
- Jachimowski, C.J. "Chemical Kinetic Mechanism for the Combustion of Propane," Comb. Flame 55, 213-224, 1984.
- Tacina, R.R., "Low NOx Potential of Gas Turbine Engines," AIAA Paper No. 90-0550, 1990.
- Mehta, J.M., Shin, H., and Wisler, D. "Mean Velocity and Turbulence Measurements in an Advanced Combustor Swirl Cup, AIAA Paper No. 89-0215, 1989.
- Roffe, G. and Venkataramani, K.S., "Experimental Study of the Effect of Cycle Pressure on Lean Combustion Emissions," NASA-CR-3032, 1978.
- Roffe, G. and R.S. Venkat Raman, "Experimental Study of the Effects of Secondary Air on the Emissions and Stability of a Lean Premixed Combustor," NASA-CR-165422, 1981
- Tacina, R.R., "Low NOx Potential of Gas Turbine Engines," AIAA Paper No. 90-0550, 1990.